DESIGN AND CONTROL OF A FULLY AUTOMATED VEHICLE DOOR

A Senior Scholars Thesis

by

KYUNG-MIN HONG

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2010

Major: Mechanical Engineering

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Approved by:

Research Advisor:	Won-jong Kim
Associate Dean for Undergraduate Research:	Robert C. Webb

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ABSTRACT

Design and Control of a Fully Automated Vehicle Door. (April 2010)

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The objective of the research was to develop a fully automated vehicle car door that can detect any object obstructing its path during operation. A fully automated door concept has not yet been implemented in the car industry. The door, operated via a pull of the door handle, utilizes an IR sensor to detect objects in its path. The vehicle door utilizes a linear direct current (DC) actuator with a built in potentiometer to power and control the vehicle door. The built in potentiometer provides feedback to the system. Proportional integral (PI) control was implemented to the system in order to provide a smoother and safer operation. The rise time of the system is 0.77 seconds and settling time is 1.07 seconds. The operation time is 3 seconds for the door to either open or close. The automated door has greater benefits compared to a manually operated door, such as ensuring greater safety in door operation and enhancing the lifetime as the door will not be slammed during its cycle. In addition, the door will provide more convenience to

physically challenged people, as they will be able to open and close the door with the push of a button.

ACKNOWLEDGMENTS

First, I would like to thank my advisor, Dr. Kim, for providing support and encouragement on my research. I am especially thankful for his gladly accepting to be my research advisor for the undergraduate research program. Whenever I was frustrated with the progress of the research, Dr.Kim not only gave me the technical advice but also gave me the confidence to finish this research. His broad knowledge in mechanical systems, electronic systems and control systems helped me design and construct this system. Thank you for spending hours every week discussing and suggesting possible solutions to my research.

I would also like to thank my lab partners from Mechatronics, Edgar Galvan and Pushkar Gokhale, for helping me design and construct the vehicle door. Without their help, I would not have been able to build the fully automated door system. A good friend, Philip Manning, was kind enough to help me transport the demo vehicle door using his truck.

I appreciate my parents, Jin-Ki and Myung-Sun, for being there when I needed them. Without their support, I would have not been able to experience the academics at Texas A&M. They were there to inspire me when I was stressed about school work.

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CHAPTER I

INTRODUCTION

Even the most advance commercially available automobile power doors are limited to operate only to close. In fact, power doors are only available on the Rolls Royce Phantom [1].There is also a system called a Soft Close, which automatically closes the door when the door is not fully closed [2].The limitation of the conventional power door is due to the lack of integrating sensors into the automation system. Compared to the conventional design the fully automated door is capable of both closing and opening with a push of a button. In addition, the door has the capability of detecting objects. The fully automated door has various advantages compared to conventional manual doors. First, the door can assist the physically challenged. Many physically challenged people use minivans equipped with power sliding doors to facilitate entry of the vehicle. The fully automated hinged doors would enable the physically challenged to drive any automobile. Second, the fully automated door prevents children from dinging other automobiles. Third, the lifetime of the system will also enhanced, as the door will not be slammed during its cycle. Furthermore, it is convenient to load luggage into the back seats using the power doors.

Linear actuator

Linear actuators are used in a wide selection of applications [3]. The lead screw linear actuator used in this research is powered by a DC motor. The gearbox in the actuator converts rotational motion generated by the DC motor to a linear motion [4]. The Force

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This thesis follows the style of *IEEE Transactions on Automatic Control*.

generated by the motor can be expressed in terms of the speed and voltage. The linear actuator has a maximum input voltage of 12V, and maximum load capacity of 20 pounds, which is sufficient force to motivate vehicle doors. A pulse width magnitude (PWM) signal generated by the PIC micro controller controls the velocity of the motor. In order to maintain the door at a constant angular velocity, the force applied by the linear actuator must vary with respect to change in the location. The actuator extends 4 inches in 2 seconds at its maximum speed. The potentiometer located inside the actuator supplies feedback to the system. This information is used to change the input voltage to the system such that it will follow the desired value. By properly controlling the speed of the linear actuator, the motion of the door can operate smoothly.

Proposed design

The test bed consists of a car door, actuator, sensors, PIC microcontroller, power supply and a mount. The design requirements for the test bed were that it be strong enough to support the weight of the door, have a stable base with a low center of gravity and be mobile. To achieve mobility a cart was built on which the rest of the test bed could be constructed. The door was mounted onto a wooden poll, which was chosen to make it convenient to change the location of the actuator mount. The poll was attached upright to one end of the cart, and then concrete was poured on the base to stabilize the poll and lower the center of gravity of the test bed. The door was attached to the poll using hinges. The actuator was fixed to the exterior of the door and the poll using the hinges provided by the actuator manufacturer. Fig. 1 shows a picture of the actual system. The IR sensor was placed on the lower part of the outside of the door with an offset angle of 15 degrees. The L298 chip was used to drive the motor in a bidirectional mode. The L298 datasheet provides a suggested circuit diagram for bidirectional DC motor as shown in Fig. 2 [5].

Fig. 1. Automated vehicle door system.

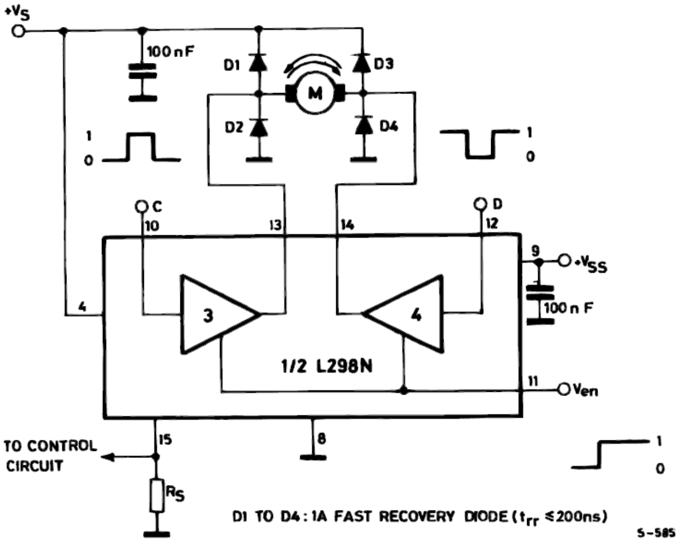

Fig. 2. Suggested circuit diagram for bidirectional DC motor control of L298N [5].

Control

The difficulty of the research was modeling the vehicle door. Due to the location of the linear actuators mount, the force acting on the door changes with respect to its position. In addition, unlike a conventional DC motor the force cannot be expressed solely in terms of speed. In this case, the Force generated from the linear actuator is a function of speed and voltage. This is more similar to an alternating current (AC) motor according to the Feedback Controls of Dynamic Systems book [6]. A classical PI controller was used to control the dynamic error. The proportional control alters the feedback to be linearly proportional. It is possible to alter the natural frequency of the system using proportional control. The implementation of position based velocity control added smoothness to the operation of the door. Without the velocity control, the door would open at full power right from the beginning, which creates vibration and jerky motion. The door reaches its maximum velocity linearly using position based velocity control. The motion shown in Fig. 3, trapezoidal velocity profile, is popular in the industry.

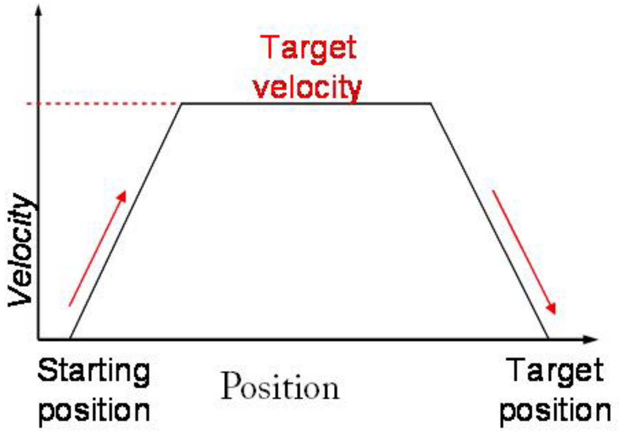

Fig. 3. Trapezoidal velocity profile [7].

CHAPTER II

ELECTROMECHANICAL DESIGN

Mechanical design

The mechanical design of this fully automated is based on a conventional power gate opener as shown in Fig. 4.

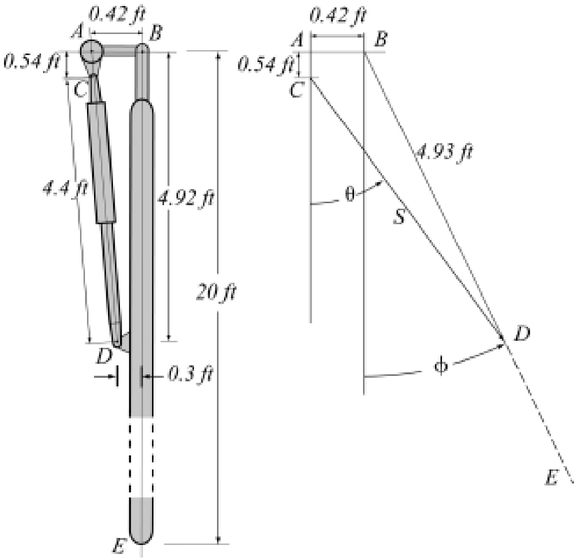

Fig. 4. Power gate opener mechanism [8].

This design differs from conventional powered vehicle doors in that it uses a linear motor instead of a rotary motor. Using a rotary motor to power doors requires different hinge designs for both the car frame and the door. Adapting the power gate design allows the ease of adaptability without drastic changes in design. In fact, the power pack can be fitted inside the door by replacing door brake with linear actuator. Fig. 5 shows the location of the door brake in conventional vehicle doors. For comparison, Fig. 6 shows how the linear actuator was actually mounted.

Fig. 5. Mounting location of the linear actuator.

Fig. 6. Door brake in conventional vehicle doors.

One of the disadvantages of using this design is the difficulty of controlling the angular velocity of the vehicle door. The constant velocity of the linear actuator will result in rapid opening rate as the vehicle door reaches its maximum opening as shown in Fig. 7 [8]. Thus, the powered door requires a system that controls the velocity of the linear actuator.

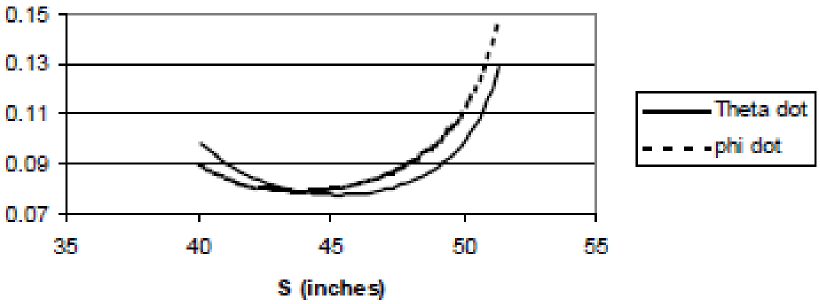

Fig. 7. Angular velocity of the door with a constant speed linear actuator [8].

Electronics design

Circuit design

The fully automated vehicle door uses a PIC 16F87 micro controller to control the motion of the door. It has multiple input and output ports that control the operations of linear actuator by receiving signals from the sensors. Signals received from the sensors were converted by a built in10 bit analog to digital converter. Computations were handled by a 20 MHz CPU that provided adequate computation time for controlling the system.

The fully automated door requires two different power sources. One power source is provided from the microcontroller breadboard, which powers the integrated chip and sensors. Mean while the linear actuator is powered by the Agilent power supply because of the higher voltage requirement.

All outputs from the sensors are handled from the PIC micro controller. The output from IR sensor connects to port A0, which converts the analog signal to a 10 bit digital signal. Likewise, the feedback from the potentiometer connects to port A1.

In order to operate the vehicle door to either open or close a full bridge L298 IC chip was used for bidirectional motor control. The operating direction is controlled by the combination of the two inputs shown in Table 1[5]. Connecting the inputs of the L298 chip to the outputs ports B5 and B6 of the PIC microcontroller enables users to change the operation direction on the fly.

TABLE 1
Function chart for bidirectional DC motor control [5].

Inputs		Function
V_{en} = H	C = H ; D = L	Forward
	C = L ; D = H	Reverse
	C = D	Fast Motor Stop
V_{en} = L	C = X ; D = X	Free Running Motor Stop

L = Low H = High X = Don't care

The PWM output from the PIC microcontroller port C2 connects to chip enable. Turning the chip on and off will have the same effect of connecting the PWM output to a motor. Additionally, two 100 kΩ resistors and two 100μF capacitors were used to regulate the voltage from the power supply. Fig. 8 shows the computer generated schematic of the circuit and Fig. 9 shows the actual implementation of the circuit.

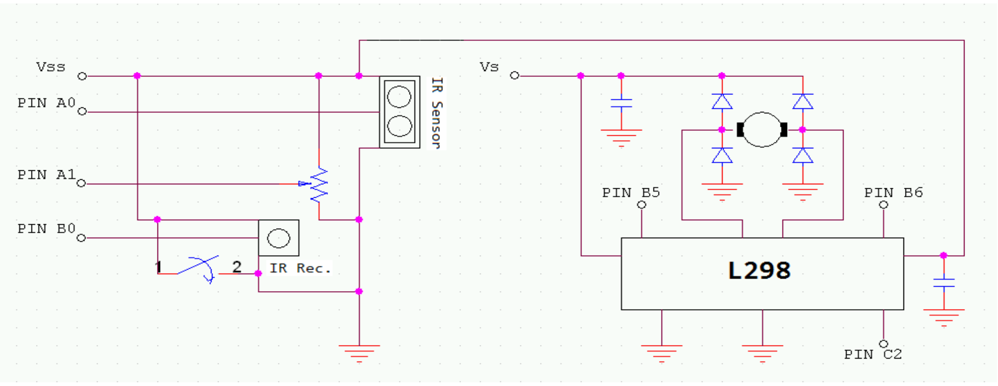

Fig. 8. Computer generated schematic of the circuit.

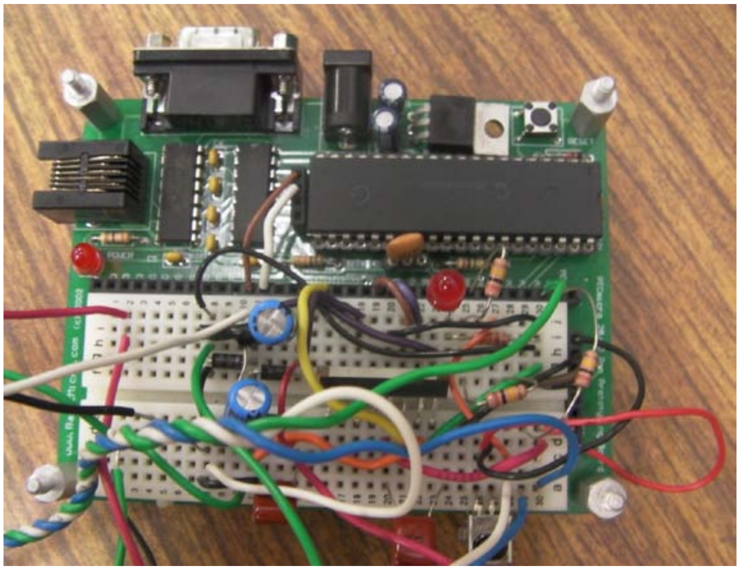

Fig. 9 Circuit design of the fully automated door.

IR sensor

A Sharp GP2Y0A02YK IR sensor was used to detect any objects when the door is in operation. The sensor has a detection range of 20cm to 150cm, which is an adequate range for detecting objects of the vehicle door. The sensor outputs a voltage value corresponding to the distance [9]. As shown in Fig. 8 the IR sensor is connected to port A0 of the PIC microcontroller, which converts the output voltage into a 10 bit number. Normally without an object obstructing the sensor, the output will read a number lower than 100. However, if an object obstructs the sensor the IR sensor will read numbers beyond 100. The automatic stop is implemented into the software by placing an immediate stop function when the IR sensor reads a number higher than 100. The code shown in APPENDIX A shows an example C code that converts the analog value read from IR sensor to a digital number.

Potentiometer

The linear potentiometer built into the actuator is a variable resistance resistor that can be used to measure the position of the door. The resistance of the resistor varies corresponding to the position of the linear actuator. Using the 5V power output from the PIC micro controller's power supply and the A/D converter, the position of the door can be indicated from the 10-bit number readings. The potentiometer is also used to calculate the velocity of the door by taking the difference of position in a set time.

The following example code shows the implementation of position based velocity control in C.

```
adc_pot = read_adc();
value=18*adc_pot+180;
set_pwm1_duty(value);
```

The PWM value changes with respect to the digital reading from the potentiometer.

Software

The logic diagram shown in Fig. 10 explains the main functionality of the program, which was constructed in C.

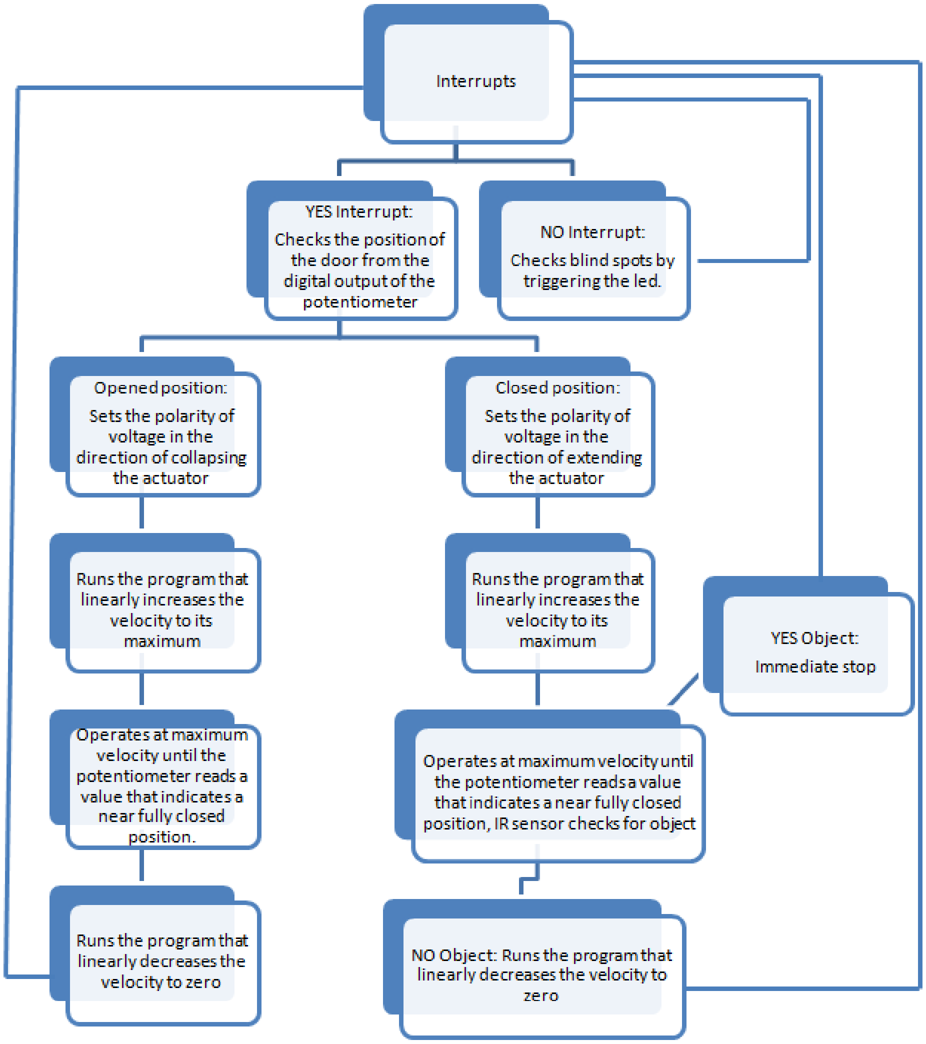

Fig. 10. Logic diagram.

First, the program continuously checks for interrupts. The system is running in idle mode when there is no interrupt. The interrupt service routine is triggered by pulling the vehicle door handle. A normally open switch inside the door handle was connected between the output of a high signal and the interrupt port. Therefore when the button on the switch is pressed by opening the door handle the signal goes from high to low, which triggers the interrupt service routine. Inside the interrupt service routine, it first checks for the position of the door using the potentiometer. When the door is in the opened position, the output ports B5 and B6 is in combination in which the motor operates in the direction of collapsing the door. Inside the interrupt service routine the program linearly increases the velocity of the door to its maximum. The maximum speed of the door is maintained until the speed decreases near the final position. Likewise, when the door is in the closed position, the PIC microcontroller runs a series of program that opens the door. The difference is when opening the door the program constantly checks for obstruction. If the program detects an object, it immediately stops. Otherwise, the program finishes its operation by fully opening the door. Appendix B shows the full program of the open loop system

CHAPTER III

CONTROLLER DESIGN

In this chapter, the system modeling of the car door is presented. The system model was used to design a closed loop controller. The controlled variable in this system, which is speed, is measured by the linear actuator's built in potentiometer. The measured speed is directed back to the system controller, to influence the output of the system. Utilizing a feedback control, the angular velocity of the door will be more precise to the desired motion profile. Compared to an open loop system, the automatic door with feedback control will be able reduce steady state errors to disturbances such as wind acting on the door. Even in harsh conditions, the closed loop controller will prevent abrupt changes in angular velocity of the door.

Linear actuator modeling

The linear actuator used for the automatic door utilizes a DC motor and a worm drive to create force in a linear motion. It does not behave like a conventional DC motor because of the friction in the gearbox. Instead, the linear actuator was modeled using the elementary analysis method used to model alternating current (AC) induction motor [6]. The equation of an AC motor is approximated as a linear equation shown below.

$$F = K_1 V_a - K_2 \dot{X} \tag{1}$$

The constant K_1 represents the ratio of change in force to a change in voltage at zero speed and K_2 represents the average ratio of change in force to a change in speed. Variable F represents force and $\dot{X}$ represents speed of the linear actuator. The units for

F is in N and $\dot{X}$ in m/s. To find the appropriate values for the constants K_1, K_2 the linear actuator was calibrated by loading different dead weights. In order to find the force as a function of actuator speed and voltage, the linear speeds of the actuator were calculated with the actuator loaded with different weights. In addition, the linear actuator was powered with different voltage levels for each load. The voltage varied from 12 volt to 6 volt in one-volt increments. The five dead weights used in this experiment were 0.28kg, 0.90kg, 1.98 kg, 3.78kg, and 4.72kg. A PIC 16F87 micro controller and an IR sensor were used in this experiment to accurately measure the total time for the linear actuator takes to reach a certain height. To achieve the linear speed of the actuator the travel length was divided by the total run time. The experiment was repeated three times to ensure accuracy.

The PIC micro controller was programmed in C. Inside the program timer 1 is initiated simultaneously with the linear actuator by outputting a high signal to the ULN 2803 chip. The timer 1 stops once the IR signal reads a value higher than 100. Timer 1 is a 16-bit timer, which overflows every 0.0262 seconds with an internal clock of 10mhz[10]. The outputted time from the PIC micro controller is the total run time for the dead weights to pass the IR beam. Fig. 11 shows the electronic schematic of the experiment and Fig. 12 shows the test bed of the experiment.

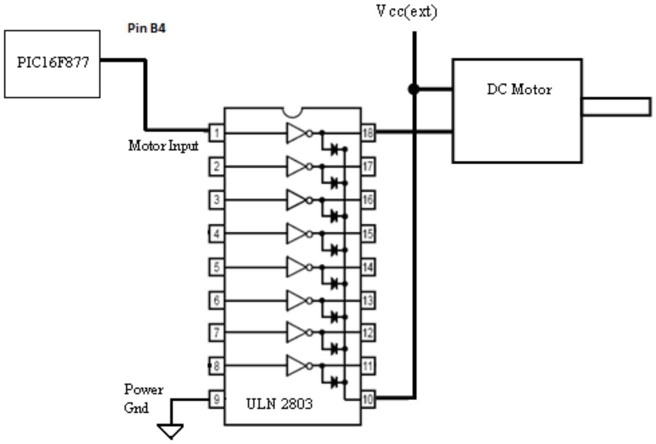

Fig. 11. Electronic schematic of the linear actuator calibration experiment [11].

Fig. 12. The test bed of the linear actuator calibration.

Linear regression analysis was performed to the graph shown in Fig. 13 to find the correlation between force, speed, and voltage of the linear actuator.

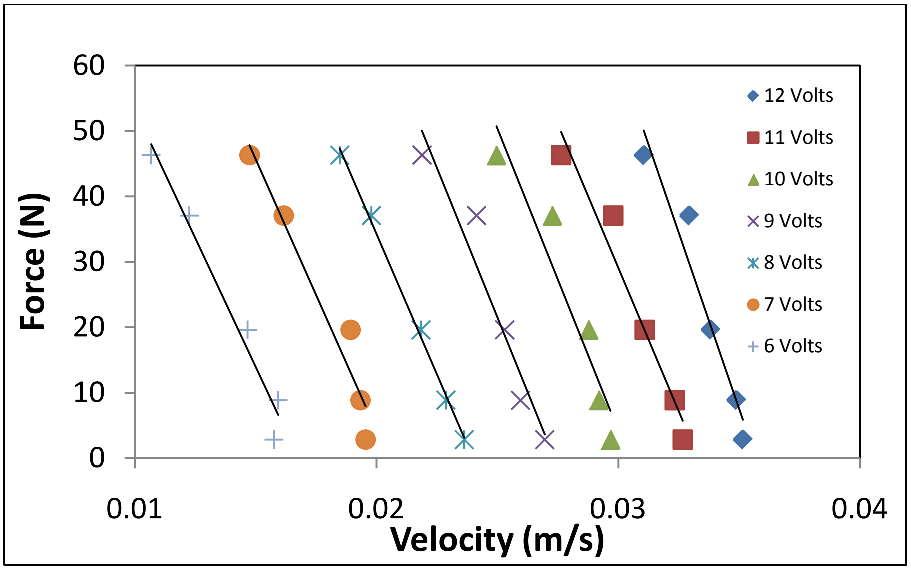

Fig. 13. The force generated from the linear actuator with different power levels and loads.

In order to find constants K_1, and K_2 the slope of the linear lines for different power levels was assumed to be equal. Thus, K_2 was assumed the average slope of linear lines. In addition, the relation between y intercepts of the linear lines with respect to voltage was calculated to find constant K_1. The results are shown in Table 2.

TABLE 2

Correlation constants for the linear actuator.

Correlation Constants	
K_1	K_2
27.7	8949

Vehicle door modeling

Using a linear actuator to power the vehicle door required complex modeling compared to mounting a rotary motor to the hinges of the door. The linear actuator is connected to the vehicle door as shown in Fig. 14. Furthermore, the connection diagram is shown in Fig. 15. In the connection diagram, variable x indicates the length of the linear actuator. The length from the hinge of the door to the bracket of the linear actuator is represented as constant a and the length from the hinge of the door to the other end of the bracket of the linear actuator is represented as constant b.

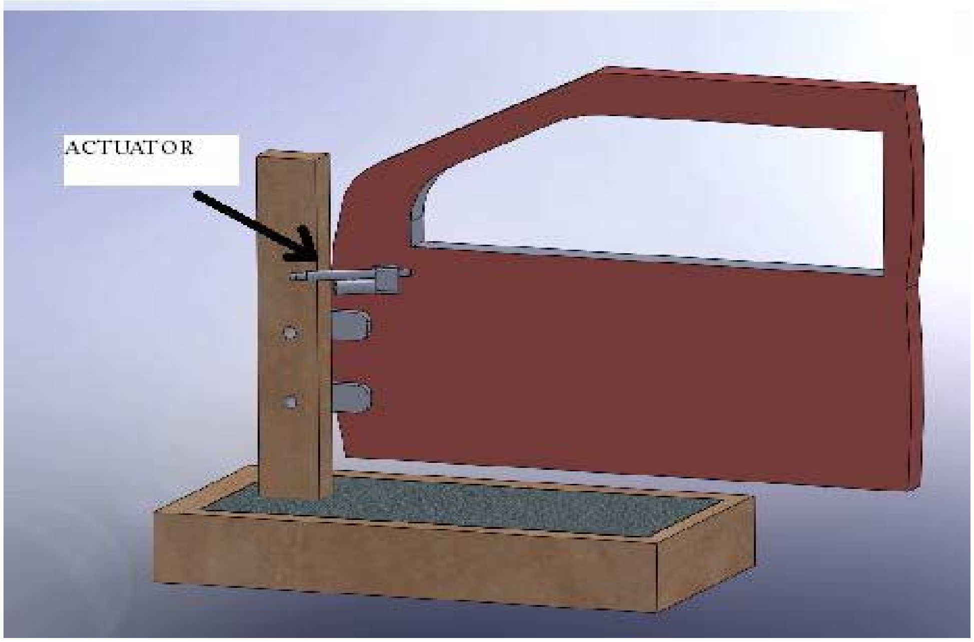

Fig. 14. The linear actuator is mounted on the frame of the vehicle door.

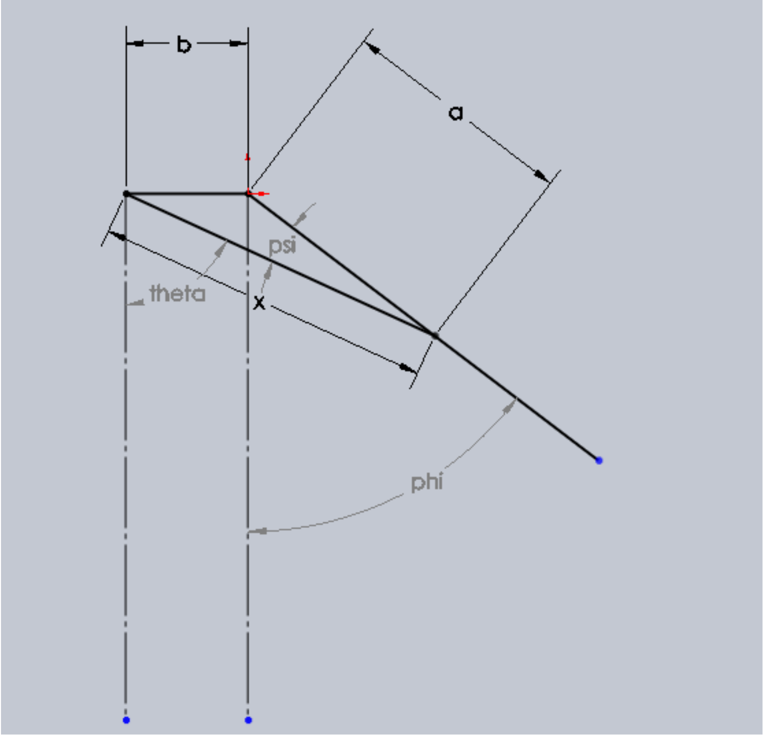

Fig. 15. The connection diagram of the linear actuator and vehicle door.

From the connection diagram, the following equation motion can be derived. Friction in the hinges was neglected in the equation of motion. The force is generated by the linear actuator.

$$I\ddot{\phi} = F\left\{\sin(\psi)\right\}a \tag{2}$$

The moment of inertia of the door was modeled as a rod with the axis of rotation at the end of the rod. The following equation is the moment of inertia equation.

$$I = \frac{mL^3}{3} \tag{3}$$

The mass of the door is 45.5kg and the length of the door is 1.23m. Parameter a is 20cm and b is 13cm.

The variables in the equation of motion required to be expressed in terms of x, due to the sensor location. In this system, a potentiometer kept track of the position and velocity of the door. In order to express psi and phi in terms of x the following steps were followed. First, psi can be expressed in terms of phi and theta using the geometrical relation.

$$\psi = \theta - \phi \tag{4}$$

Derived from trigonometry identities sin($\theta - \phi$) can be expressed as

$$\sin(\theta - \phi) = \sin(\theta)\cos(\phi) - \cos(\theta)\sin(\phi) \tag{5}$$

The expression will be further broken down using the kinematic constraints of the system.

$$x\sin(\theta) = b + a\sin(\phi) \tag{6}$$

$$x\cos(\theta) = a\cos(\phi) \tag{7}$$

Squaring both the left and right hand sides of the equation 5 and equation 6 and summing them up respectively will result in equation 7.

$$x^2\sin^2(\theta) + x^2\cos^2(\theta) = b^2 + a^2\sin^2(\phi) + 2ab\sin(\phi) + a^2\cos^2(\theta) \tag{8}$$

The equation can be reduced to the expression

$$x^2 = b^2 + a^2 + 2ab\sin(\phi) \tag{9}$$

Furthermore, $\sin(\phi)$ can be expressed in terms of x

$$\sin(\phi) = \frac{x^2 - b^2 - a^2}{2ab} \tag{10}$$

To express $\cos(\phi)$ in terms of x the following relation will be used

$$\cos\left\{\arcsin\left(\frac{x^2-b^2-a^2}{2ab}\right)\right\}=\frac{1}{2}\sqrt{\left(\frac{4-(x^2-b^2-a^2)^2}{(a^2b^2)}\right)} \tag{11}$$

Similarly, $\sin(\theta)$, and $\cos(\theta)$ can be expressed in terms of x using equation 5 and 6

$$\sin(\theta)=\left(\frac{b+a\dfrac{x^2-b^2-a^2}{2ab}}{x}\right) \tag{12}$$

$$\cos(\theta)=\left(\frac{a\sqrt{\left(\dfrac{4-(x^2-b^2-a^2)^2}{(a^2b^2)}\right)}}{2x}\right) \tag{13}$$

The only variable that is not in terms of x in the equation of motion is $\ddot{\phi}$. Taking the second time derivative on both sides of equation 14 $\ddot{\phi}$ can be expressed in terms of x.

$$\phi=\arcsin\left(\frac{x^2-b^2-a^2}{2ab}\right) \tag{14}$$

The result is shown in equation 15.

$$\ddot{\phi} = \left\{ \frac{2}{ab\sqrt{4-\frac{(x^2-b^2-a^2)^2}{a^2b^2}}} + \frac{4x^2(x^2-b^2-a^2)}{a^3b^3\left(4-\frac{(x^2-b^2-a^2)^2}{a^2b^2}\right)^{\frac{3}{2}}} \right\}\dot{x}^2 + \frac{2x}{ab\sqrt{4-\frac{(x^2-b^2-a^2)^2}{a^2b^2}}}\ddot{x} \tag{15}$$

Combining all calculations, the equation of motions can be wrote in terms of x

$$I\left[\left\{ \frac{2}{ab\sqrt{4-\frac{(x^2-b^2-a^2)^2}{a^2b^2}}} + \frac{4x^2(x^2-b^2-a^2)}{a^3b^3\left(4-\frac{(x^2-b^2-a^2)^2}{a^2b^2}\right)^{\frac{3}{2}}} \right\}\dot{x}^2 + \frac{2x}{ab\sqrt{4-\frac{(x^2-b^2-a^2)^2}{a^2b^2}}}\ddot{x}\right] = Fa\left[\left(\frac{b+a\frac{x^2-b^2-a^2}{2ab}}{x}\right)\frac{1}{2}\sqrt{\left(\frac{4-(x^2-b^2-a^2)^2}{(a^2b^2)}\right)} - \left(\frac{a\sqrt{\left(\frac{4-(x^2-b^2-a^2)^2}{(a^2b^2)}\right)}}{2x}\right)\frac{x^2-b^2-a^2}{2ab}\right. \tag{16}$$

Linearization

Similar to most practical systems the automated vehicle door is a non-linear system. Since linear systems are easier to handle than nonlinear systems, the system’s equation of motion will be linearized. The linearization process, which was developed by Lyapunov, is process of approximating a nonlinear system with a linear model [12]. According to Lyaprunov, if a linearized approximation has all roots in the left half plane there exists a region near equilibrium point where the nonlinear system is stable[13]. Within the region of stability, one can use the linearized model for small signals.

The following steps show the process of linearization for the automated door system using small signal analysis. The system equation is expressed in the following form, where the function ‘f’ is in non linear form.

$$\ddot{x}(t) = f(x(t), \dot{x}(t), u(t)) \tag{17}$$

In order to obtain the equilibrium point of the system all derivatives was equated to zero.

$$\dot{x}(t) = 0, \ddot{x}(t) = 0 \tag{18}$$

For an input force that has a nominal value of $u_0 = 0$, the equilibrium position can be calculated. As seen in equation 16, the system has multiple equilibrium points with the input force zero. This is intuitive since the door is in equilibrium at any position with nominal input force. In this case, the equilibrium point was chosen to be the initial point $x_0 = 23.8$. The initial point is when the door is in the closed position. In other words, it is when angle phi is zero degrees. The following equation was used to calculate the first equilibrium point, where a equals to 20cm and b equals to 13cm.

$$x_0 = sqrt(a^2 + b^2), \phi = 0^\circ \tag{19}$$

The next step was to expand the non-linear equation 16 using the Taylors series about the equilibrium points as shown in equation 19.

$$\begin{aligned}\ddot{x}(t) = {} & f(x_0,u_0) + \left.\frac{\delta f}{\delta x}\right|_{\substack{x=x_0\\ \dot{x}=\dot{x}_0\\ u=u_0}} \cdot (x(t)-x_0) + \cdots \\ & + \left.\frac{\delta f}{\delta u}\right|_{\substack{x=x_0\\ \dot{x}=\dot{x}_0\\ u=u_0}} \cdot (u(t)-u_0) + \cdots \\ & \left.\frac{\delta f}{\delta \dot{x}}\right|_{\substack{x=x_0\\ \dot{x}=\dot{x}_0\\ u=u_0}} \cdot (\dot{x}(t)-\dot{x}_0) + \cdots\end{aligned} \tag{20}$$

This calculation was performed in Maple as shown in APPENDIX C. The final result is shown in equation 21 with the units in cm/s for $\dot{x}$.

$$\Delta\ddot{x} = 0.5513 \cdot \Delta V - 2.004 \cdot \Delta\dot{x} \tag{21}$$

Control design

The time dependent governing equation is transformed into the frequency domain using Laplace transform. Zero conditions, x(0) = $x'(0)$ = 0, must be assumed when finding the transfer function [6]. The result of performing the Laplace transform of the governing equation is shown in equation 22.

$$s^2 X(s) = 0.5513 \cdot V(s) - 2.004 \cdot sX(s) \tag{22}$$

The equation is rearranged in order to find the transfer function, which is defined as the output X over the input V.

$$\frac{X(s)}{V(s)} = \frac{0.5513}{s^2 + 2.004s} \tag{23}$$

In this case, the transfer function between the motor input and the output speed is required. Taking the derivative with respect to time in the time domain is equivalent to multiplying the transfer function by s in the frequency domain.

$$\frac{\dot{X}(s)}{V(s)} = \frac{0.5513}{s+2.004} \tag{24}$$

In order to analyze the original open loop system performance, the transient step response was plotted in Matlab as shown in Fig. 16.

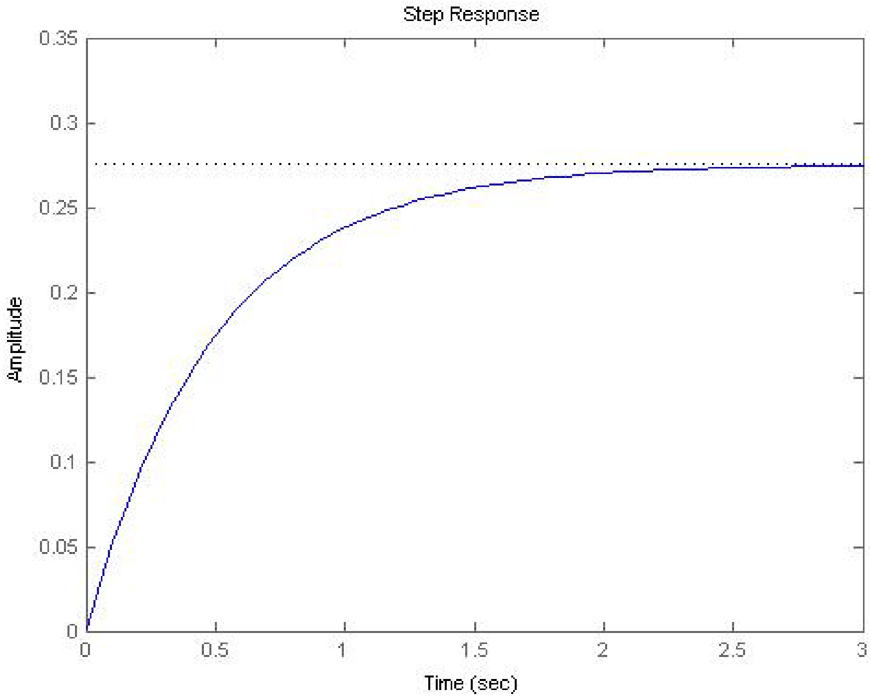

Fig. 16. Open loop step response of the system.

The rise time was 1.097 seconds and settling time was 1.9523 seconds. Furthermore, steady state error is present. In order to reduce the steady state error and decrease rise time, a proportional-integral (PI) controller was designed using root locus. The following equation is the controller designed for fully automated system.

$$D(s) = \frac{K_p s + K_i}{s} = \frac{3.5s + 10}{s} \tag{25}$$

As shown in Fig. 17 the root locus of the system has a damping ratio of 0.839 and system natural frequency of 2.35rad/s.

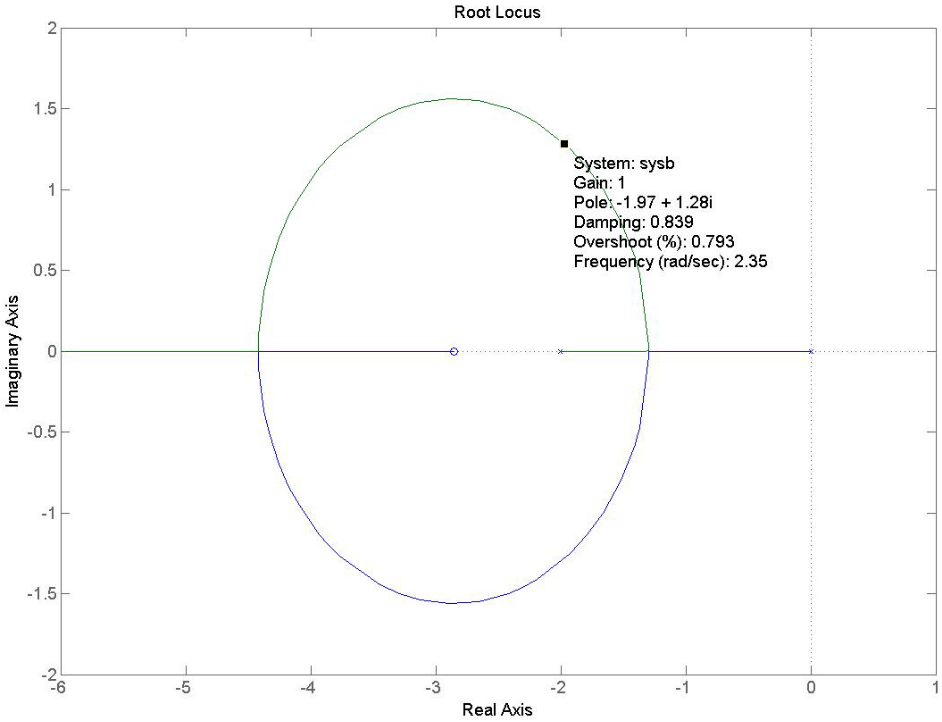

Fig. 17. Closed loop system root locus.

The PI control drastically reduced the steady state error and decreased the rise time as shown in Fig. 18 and Table 3.

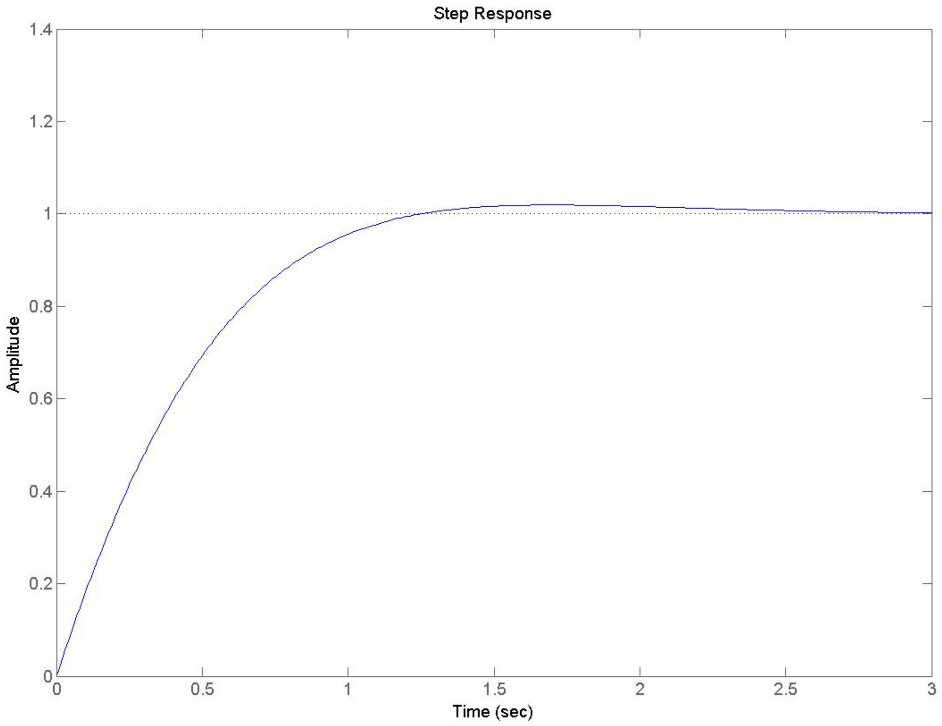

Fig. 18. Closed loop step response of the system.

TABLE 3

Dynamic performance of the closed loop system.

Rise Time (S)	***0.7769***
Percentage Overshoot (%)	***1.9338***
Settling Time (S)	***1.1099***

A discrete-time controller was required to implement the control system in the PIC micro controller. The controller was obtained based on the Tustin’s method [6]. This method is sometimes called emulation since the continuous control is digitalized instead of designing the digital control from the ground up. Digital controller requires the sampling frequency to be at least 25 times the bandwidth of the system in order to match the continuous controller[6]. The system bandwidth of the fully automated door was determined to be 2.68 rad/s. Thus, the sampling frequency should be at least 67.25rad/s, which is equivalent to 10.7 Hz. The following discrete-time controller was obtained using MATLAB “c2d” command with sampling period of 0.1 seconds. The continuous controller parameters were deliberately chosen to set the discrete-time controller parameters as integers, which reduces the computation time of the PIC microcontroller. According to the complier manual, the system requires 16 times more computation time for floating point addition compared to 16-bit integer [10]. Equation 26 shows the discrete time controller used in the system.

$$u(k) = u(k-1) + 4e(k) - 3e(k-1) \tag{26}$$

Discrete time control implementation

The discrete time controller was implemented into the program using the commands shown in APPENDIX D. The desired speed is set by the variable u2 in units of cm/s. Factor 0.027 is used to convert the output speed to cm/s. The command shown below is the implementation of the discrete time controller in the program.

```
u=u1+4*e-3*e1;
```

(27)

The past value of control u1 and past value of error is saved every time the program runs a loop.

Dynamic performance

The usability of the door was evaluated by measuring the dynamic performance. As shown in Table 4, it took 3.3 seconds to open the door from the closed position. The maximum opening angle of 35 degrees provided an adequate space for the passengers to get into the car.

TABLE 4
Dynamic performance of the system.

Dynamic Performance	
Total Time to Open (s)	3.3
Total Time to Close (s)	3.3
Average Angular Velocity(Rad/s)	0.2035
Maximum Opening Angle (Degrees)	35

CHAPTER IV

CONCLUSIONS

In this thesis, the design, construction, and testing of the fully automated vehicle door were discussed. The system consists of three main components including an IR sensor, linear actuator, and PIC micro controller. The IR sensor has a detection range of 20cm to 150cm. The fully automated door is capable of either opening or closing by utilizing the L298 chip. Modeling the vehicle door was more complicated compared to a mechanism with a rotary motor. However, the power gate mechanism is more adaptable to conventional vehicle doors. The model of the linear actuator was determined to be similar to an AC motor through experimentation. The force created from the actuator was a function of speed and voltage. The vehicle door was capable of opening and closing in 3.3 seconds. The rise time of the closed loop system was 0.77 seconds. The bandwidth of the system was 2.68 rad/s, which was low enough for the 20Mhz CPU to handle.

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APPENDIX A

SAMPLE PROGRAM FOR IR SENSOR

```
#include <16F877.h>
#device ADC=10
#use delay(clock=10000000)
 #use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7)
main()
{
long adc_value;
 setup_adc_ports(RA0_ANALOG);
setup_adc(ADC_CLOCK_INTERNAL);
while (1)
{
set_adc_channel(0);
delay_us(10);
adc_value = read_adc();
printf("%lu\n\r", adc_value);
}
}
```

APPENDIX B

OPEN LOOP PROGRAM FOR FULLY AUTOMATED DOOR

```
#include <16F877.h>
#device ADC=10
#use delay(clock=10000000)
#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7)

#INT_EXT
External_Interrupt()

{
long adc_pot; //port A1
long value;
long adc_ir; //port A0
long adc_pot0;
setup_ccp1(CCP_PWM);
setup_timer_2(T2_DIV_BY_1, 255, 1);
printf("External Interrupt !\n\r");
delay_ms(100);                      //lets us read that the interupt
value=1023; //speed control


set_adc_channel(1);
delay_us(100);
adc_pot = read_adc();


if (adc_pot<100)
                              {

set_adc_channel(0);
delay_us(100);
adc_ir= read_adc();
while( adc_pot<45)
{
output_low(PIN_B5);
output_high(PIN_B6);
set_adc_channel(1);
delay_us(100);
adc_pot = read_adc();
value=18*adc_pot+180;
set_pwm1_duty(value);
printf("open v %ld \n\r", value);
delay_us(100);
}
while(adc_ir<200 && adc_pot<850)
                  {
output_low(PIN_B5);
output_high(PIN_B6);
set_pwm1_duty(value);
```

```
delay_us(100);
set_adc_channel(0);
delay_us(200);
adc_ir= read_adc();

delay_us(100);
set_adc_channel(1);
delay_us(100);
adc_pot = read_adc();
printf(" open adc ir: %ld adc pot: %ld \n\r", adc_ir, adc_pot);

                  }
while( adc_pot>850 && adc_pot<860 )
{
output_low(PIN_B5);
output_high(PIN_B6);
set_adc_channel(1);
delay_us(100);
adc_pot = read_adc();
value=-33*adc_pot + 28182;
set_pwm1_duty(value);
printf(" v %ld \n\r", value);
delay_us(100);
}


output_low(PIN_B5);
output_low(PIN_B6);
delay_ms(100);

                              }



else
                        {
set_adc_channel(1);
delay_us(100);


while(adc_pot>50  )
                              {
output_high(PIN_B5);
output_low(PIN_B6);
delay_us(100);
adc_pot= read_adc();
set_pwm1_duty(1023);
printf("close adc pot: %ld \n\r", adc_pot);

                              }
while(adc_pot>30)
                              {
output_high(PIN_B5);
output_low(PIN_B6);
```

```
delay_us(100);
adc_pot= read_adc();
value=24*adc_pot-182;
set_pwm1_duty(value);
printf("close v: %ld \n\r", value);

                              }
                        }
output_low(PIN_B5);
output_low(PIN_B6);
delay_ms(100);
}
main()
                                    {
long adc_ir;
ext_int_edge(H_to_L);
enable_interrupts(INT_EXT);
enable_interrupts(global);
setup_port_a(ALL_ANALOG);
setup_adc(ADC_CLOCK_INTERNAL);





while(1)
{
set_adc_channel(0);
delay_us(100);
adc_ir = read_adc();
printf("still adc ir: %ld \n\r", adc_ir);
if (adc_ir>50)
            {

output_high(PIN_B2);
            }
else
output_low(PIN_B2);
```

APPENDIX C

COMMANDS FOR LINEARIZATION CALCULATION

Commands for $\left.\dfrac{\delta f}{\delta x}\right|_{\substack{x=x_0\\ \dot{x}=\dot{x}_0\\ u=u_0}}$ calculation in Maple

$$> \mathit{assign}\left(q = \frac{2}{a\cdot b\cdot \mathrm{sqrt}\left(4 - \dfrac{\left(x^2-b^2-a^2\right)^2}{a^2\cdot b^2}\right)} + \frac{4\cdot x^2\left(x^2-b^2-a^2\right)}{a^3\cdot b^3\left(4-\dfrac{\left(x^2-b^2-a^2\right)^2}{a^2b^2}\right)^{\frac{3}{2}}}\right)$$

$$> \mathit{assign}\left(z = \frac{2\cdot x}{a\cdot b\cdot \mathrm{sqrt}\left(4 - \dfrac{\left(x^2-b^2-a^2\right)^2}{a^2\cdot b^2}\right)}\right)$$

$$> \mathit{assign}\left(t = \left(\frac{\left(b+\dfrac{a\cdot\left(x^2-b^2-a^2\right)}{2\cdot a\cdot b}\right)}{x}\cdot\frac{1}{2}\cdot\mathrm{sqrt}\left(\frac{\left(4-\left(x^2-b^2-a^2\right)^2\right)}{a^2\cdot b^2}\right) - \left(\frac{a\cdot\mathrm{sqrt}\left(\dfrac{\left(4-\left(x^2-b^2-a^2\right)^2\right)}{a^2\cdot b^2}\right)}{2\cdot x\cdot 2\cdot a\cdot b}\right)\cdot\left(x^2-b^2-a^2\right)\right)\right)$$

$$> \mathit{assign}\left(f = 27.7\cdot v - 8949\cdot \mathit{xdot}\right)$$

$$> \mathit{diff}\left(\left(\frac{\left(\dfrac{f\cdot a}{I}\cdot t - q\cdot \mathit{xdot}^2\right)}{z}\right), x\right)$$

$$0.\ \mathrm{I}$$

Commands for $\left.\dfrac{\delta f}{\delta v}\right|_{\substack{x=x_0\\ \dot{x}=\dot{x}_0\\ u=u_0}}$ calculation in Maple

> $$assign\left(q=\frac{2}{a\cdot b\cdot \mathrm{sqrt}\left(4-\dfrac{\left(x^2-b^2-a^2\right)^2}{a^2\cdot b^2}\right)}+\frac{4\cdot x^2\left(x^2-b^2-a^2\right)}{a^3\cdot b^3\left(4-\dfrac{\left(x^2-b^2-a^2\right)^2}{a^2b^2}\right)^{\frac{3}{2}}}\right)$$

> $$assign\left(z=\frac{2\cdot x}{a\cdot b\cdot \mathrm{sqrt}\left(4-\dfrac{\left(x^2-b^2-a^2\right)^2}{a^2\cdot b^2}\right)}\right)$$

> $$assign\left(t=\left(\frac{\left(b+\dfrac{a\cdot\left(x^2-b^2-a^2\right)}{2\cdot a\cdot b}\right)}{x}\cdot\frac{1}{2}\cdot \mathrm{sqrt}\left(\frac{\left(4-\left(x^2-b^2-a^2\right)^2\right)}{a^2\cdot b^2}\right)-\left(\frac{a\cdot \mathrm{sqrt}\left(\dfrac{\left(4-\left(x^2-b^2-a^2\right)^2\right)}{a^2\cdot b^2}\right)}{2\cdot x\cdot 2\cdot a\cdot b}\right)\cdot\left(x^2-b^2-a^2\right)\right)\right)$$

> $assign\left(f=27.7\cdot v-8949\cdot xdot\right)$

> $diff\left(\dfrac{f\cdot a}{i\cdot z}\cdot t, v\right)$

$$\frac{1}{i\,x}\left(13.85000000a^2\,b\,\sqrt{4-\frac{\left(x^2-b^2-a^2\right)^2}{a^2\,b^2}}\left(\frac{1}{2}\,\frac{1}{x}\left(\left(b+\frac{1}{2}\,\frac{x^2-b^2-a^2}{b}\right)\sqrt{\frac{4-\left(x^2-b^2-a^2\right)^2}{a^2\,b^2}}\right)-\frac{1}{4}\,\frac{\sqrt{\dfrac{4-\left(x^2-b^2-a^2\right)^2}{a^2\,b^2}}\,\left(x^2-b^2-a^2\right)}{x\,b}\right)\right)$$

> $assign\left(a=0.2, b=0.13, x=\mathrm{sqrt}\left(0.2^2+0.13^2\right)\right)$

>
$$\frac{1}{i\,x}\left(13.85000000 a^2\,b\,\sqrt{4-\frac{\left(x^2-b^2-a^2\right)^2}{a^2\,b^2}}\left(\frac{1}{2}\,\frac{1}{x}\left(\left(b+\frac{1}{2}\,\frac{x^2-b^2-a^2}{b}\right)\sqrt{\frac{4-\left(x^2-b^2-a^2\right)^2}{a^2\,b^2}}\right)-\frac{1}{4}\,\frac{\sqrt{\frac{4-\left(x^2-b^2-a^2\right)^2}{a^2\,b^2}}\,\left(x^2-b^2-a^2\right)}{x\,b}\right)\right)$$

$$\frac{12.65729350}{i}$$

Commands for $\left.\frac{\delta f}{\delta \dot{x}}\right|_{\substack{x=x_0\\ \dot{x}=\dot{x}_0\\ u=u_0}}$ calculation in Maple

>
$$assign\left(q=\frac{2}{a\cdot b\cdot \mathrm{sqrt}\left(4-\frac{\left(x^2-b^2-a^2\right)^2}{a^2\cdot b^2}\right)}+\frac{4\cdot x^2\left(x^2-b^2-a^2\right)}{a^3\cdot b^3\left(4-\frac{\left(x^2-b^2-a^2\right)^2}{a^2b^2}\right)^{\frac{3}{2}}}\right)$$

>
$$assign\left(z=\frac{2\cdot x}{a\cdot b\cdot \mathrm{sqrt}\left(4-\frac{\left(x^2-b^2-a^2\right)^2}{a^2\cdot b^2}\right)}\right)$$

>
$$assign\left(t=\left(\frac{\left(b+\frac{a\cdot\left(x^2-b^2-a^2\right)}{2\cdot a\cdot b}\right)}{x}\cdot\frac{1}{2}\cdot \mathrm{sqrt}\left(\frac{\left(4-\left(x^2-b^2-a^2\right)^2\right)}{a^2\cdot b^2}\right)-\left(\frac{a\cdot \mathrm{sqrt}\left(\frac{\left(4-\left(x^2-b^2-a^2\right)^2\right)}{a^2\cdot b^2}\right)}{2\cdot x\cdot 2\cdot a\cdot b}\right)\cdot\left(x^2-b^2-a^2\right)\right)\right)$$

>
$$assign\,(f=27.7\cdot v-8949\cdot xdot)$$

> $\mathit{diff}\left(\mathit{diff}\left(-\frac{t\cdot \mathit{xdot}^{2}}{z}, \mathit{xdot}\right), \mathit{xdot}\right)$

200.47

APPENDIX D

CLOSED LOOP PROGRAM

```
#include <16F877.h>
#device ADC=10
#use delay(clock=10000000)
#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7)

#INT_EXT


External_Interrupt()

{
long cnt = 0;
long speed = 0;
long u1=0;
signed long e1=0;
long u2=3 ;
signed long e;
signed long u;
long x;
long adc_pot; //port A1
long adc_pot1; //port A1
long adc_pot2; //port A1
long value;
long adc_ir; //port A0
long adc_pot0;
setup_ccp1(CCP_PWM);
setup_timer_2(T2_DIV_BY_1, 255, 1);
printf("External Interrupt !\n\r");
delay_ms(100);                      //lets us read that the interupt
value=1023; //speed control


set_adc_channel(1);
delay_us(100);
adc_pot = read_adc();


if (adc_pot<100)
                              {

set_adc_channel(0);
delay_us(100);
adc_ir= read_adc();
while( adc_pot<840)
{
```

```
output_low(PIN_B5);
output_high(PIN_B6);
speed = cnt*0.027;
set_adc_channel(1);
delay_us(100);
adc_pot1 = read_adc();
delay_ms(80);
adc_pot2 = read_adc();
cnt=(adc_pot2-adc_pot1)/0.1;
e=u2-speed;
u=u1+4*e-3*e1;
x=u;
delay_us(100);
set_pwm1_duty(x);
u1=u;
e1=e;
delay_us(100);

}

main()
                                    {
long adc_ir;
ext_int_edge(H_to_L);
enable_interrupts(INT_EXT);
enable_interrupts(global);
setup_port_a(ALL_ANALOG);
setup_adc(ADC_CLOCK_INTERNAL);





while(1)
{
set_adc_channel(0);
delay_us(100);
adc_ir = read_adc();
printf("still adc ir: %ld \n\r", adc_ir);
if (adc_ir>50)
            {

output_high(PIN_B2);
            }
else
output_low(PIN_B2);

}
                                    }
```

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